Sustainability based-approach to determine the concrete type and reinforcement configuration of TBM tunnels linings. Case study: Extension line to Barcelona Airport T1

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ABSTRACT

Fibre-reinforced concrete (FRC) is a suitable alternative to the traditional reinforced concrete used in the manufacture of precast segments used to line tunnels excavated with a tunnel boring machine (TBM). Moreover, its use as a structural material has been approved by several national codes and by the current *fib Model Code* (2010). The use of FRC in segmental linings confers several technical and economic advantages, evidenced by the fact that structural fibres have been used to partially or entirely replace reinforcing bars in many TBM tunnels built over the past 20 years or currently under construction. FRC could also have been used in other tunnels, which are currently in the planning stage or under construction. However, despite its technical suitability and approval in current codes, the use of FRC was not possible in some cases. The impediment has sometimes been an incomplete understanding of the structural behaviour of the material, but a more general motive has been that comparisons of materials have taken into account only direct material costs and have not considered indirect costs or social and environmental factors. The aim of the present research is to develop a method for analysing the sustainability of different concrete and reinforcement configurations for segmental linings of TBM tunnels using the MIVES method (a multi-criteria decision making approach for assessing sustainability). This MCDM method allows minimising subjectivity in decision making while integrating economic, environmental and social factors. The model has been used to assess the sustainability of different alternatives proposed for manufacturing the segmental tunnel lining for the extension of the rail line of Ferrocarrils de la Generalitat de Catalunya (FGC) to Terminal 1 of El Prat Airport in Barcelona.

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1. Introduction

For economic and technical reasons, the use of fibre-reinforced concrete (FRC) to partially or even entirely replace traditional steel bar reinforcement in concrete elements has increased in applications, such as floor slabs (Meda et al., 2004), suspended slabs (Pujadas et al., 2014; Blanco et al., 2015) sewerage pipes (de la Fuente et al., 2012a, 2013), reinforced earth-retaining walls (de la Fuente et al., 2010) and other more advanced applications (di Prisco et al., 2009; Walraven, 2009), particularly as a result of the inclusion of FRC in the *fib Model Code* 2010 (MC 2010) (fib, 2010). Precast concrete segments used in TBM tunnels linings (de la Fuente et al., 2012b) may be the elements that have benefited most from the use of FRC and specific examples of this new trend can be found in the literature (Caratelli et al., 2012; Meda and Rinaldi, 2014). In tunnel linings, the use of structural fibres has technical—and, more generally, economic—advantages since the tensile stresses generated in both transitional stages and service are usually low or, even, inexistent. In such cases, the use of rebar may be reduced or entirely eliminated.

Particularly in terms of design, the concrete age t during the transitional stages of demoulding, storage and transport (Fig. 1a–c) must be sufficient to ensure that tensile stresses are less than the flexural strength of the material ($f_{ct,fl}$) and that only minimal reinforcement is required to ensure adequate ductile behaviour (Plizzari and Tiberti, 2006; Chiaia et al., 2009a,b; Caratelli et al., 2011; Cignitti et al., 2012; Liao et al., 2015a) in the event of a cracking. When the tunnel is in use under standard geotechnical conditions, the lining segments are generally compressed to levels at which the material performs optimally with little likelihood of cracking, such that the amount of reinforcement needed is also reduced.

Traditional reinforced concrete linings are manufactured by inserting pre-assembled reinforcement cages into the segment mould (Fig. 2). The process is complicated by manufacturing considerations, the amount of space needed, and the lifting gear required to place the reinforcement cages, all of which increase the cost of the traditional solution. For reasons of fire resistance (Lilliu and Meda, 2013), the reinforcement cage must have an extra concrete cover from that strictly required for durability purposes. This practice sometimes results in unreinforced concrete areas. Such areas may be subject to cracks caused by local phenomena, such as bursting, spalling and splitting, along with consequent problems relating to aesthetics and durability of the material, which generally entail repairs and associated cost overruns. Such cracks are usually caused by the localised effect of concentrated loads and specific states of stresses that occur when seg-

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Fig. 1. (a) Demoulding; (b) transport and (c) stacking at the yard.

Fig. 2. Insertion of the pre-assembled reinforcement cage.

ments are subject to jacks' thrust during installation (Fig. 3) (Schnüntger and Erdem, 2001; Cavalaro and Aguado, 2012; Tiberti and Plizzari, 2014).

The use of structural fibres is an attractive solution that can enhance concrete performance in these load states (Burguers et al., 2007; Bakhshi and Nasri, 2014; Liao et al., 2015b,). If the amount (C_f) and type of fibre are correctly specified, it is possible to avoid spalling and to control the width of cracks that may be caused by dynamic impacts and, more frequently, during the ram thrusts stage.

In view of the above, the FRC segment can be designed in two different ways: (1) When the tensile stresses on the segment do not result in cracking and the stresses exerted by the ram thrusts are also low, the use of a C_f without other reinforcement may be considered (typically 30 kg/m^3 < C_f ⩽ 60 kg/m^3). (2) Alternatively, when the forces transmitted by the rams are high, hybrid reinforcement may be used, combining 20 kg/m^3 ⩽ C_f ⩽ 40 kg/m^3 with local rebar reinforcement in the area affected by ram thrust.

While the current code permits the use of fibre reinforcement in structural elements and the solution has proven to be both technically and economically attractive in the segmental linings used in over 50 TBM tunnels built to date (de la Fuente et al., 2012b), some doubts still persist concerning the use of FRC in this particular application. These doubts are mainly due to the following two factors: (1) project planners have little technical knowledge of the use of this material; (2) existing studies that compare traditional and FRC solutions are based solely on direct material costs without taking into account either indirect costs or social and environmental factors, that is, without considering the sustainability of possible solutions.

Fig. 3. Cracks detected during the installation phase involving ram thrusts.

The objective of the present research project is to propose a multi-criteria decision making (MCDM) method based on the MIVES Integrated Value Model for Sustainable Assessment. The MIVES method can be used to assess viable solutions for both concrete type and reinforcement configuration of precast concrete segments while taking into account economic, environmental and social criteria.

The MIVES method is intended to minimise subjectivity in the decision making processes through the use of value functions (Alarcon et al., 2001), and it has already been validated and used in industrial buildings (San-Jose Lombera and Garrucho Aprea, 2010; San-Jose Lombera and Cuadrado Rojo, 2010; Reyes et al., 2014), underground infrastructures (Ormazabal et al., 2008), hydraulic structures (Pardo and Aguado, 2014; de la Fuente et al., 2016), wind towers (de la Fuente et al., 2016), and construction projects (Pons and Aguado, 2012; Pons and de la Fuente, 2013). It has also been approved by the current Spanish Structural Concrete Code (CPH, 2008) as a way of assessing the sustainability of concrete structures (Aguado et al., 2012) and the model has even been expanded to include the uncertainties involved in the process of analysis (del Caño et al., 2012).

The method proposed has been used to analyse the sustainability of three different alternatives of concrete and reinforcement for the manufacturing of the tunnel lining segments used in the Ferrocarrils de la Generalitat (FGC) rail line extension to Terminal 1 of El Prat Airport in Barcelona. In the present study, different types of concrete (conventional and self-compacting) and different reinforcement scenarios are analysed, and complete the process by presenting a sensitivity study. The resulting prioritisation of alternatives has helped the technical staff responsible for constructing the tunnel to identify the solution best suited to the demands of the project.

2. Proposed method for assessing the sustainability of tunnel lining segments

2.1. General features

The method proposed is based on the MIVES model, which involves the definition of three key elements: (1) the boundaries of the system, in order to establish the scope of the analysis; (2) a tree of requirements (R), criteria (C) and indicators (I) that allows decision makers to identify the important factors that must be involved in assessing the sustainability of the type of concrete and reinforcement used in the segments, and (3) the value functions used to convert the attributes or physical units associated with each indicator to unidimensional values (ranging from 0 to 1). These values also facilitate measurement of the degree of satisfaction associated with the indicator.

A series of seminars were organised to define these three key elements. The participants were a group of experts from the public and private sectors specialised in the design and manufacture of precast lining segments. The results of these seminars were then used to define the initial requirement tree, to assign the appropriate weight to each element using the Analytic Hierarchy Process (AHP) method (Saaty, 1990), and to provide real data from projects to establish the value functions and scoring criteria for each indicator, measured in terms of attributes.

2.2. System boundaries

The three requirements under consideration are those that are generally associated with sustainability: economic, environmental, and social impact (United Nations, 2005). The possibility of including a technological requirement was also discussed. This requirement would combine such aspects as increasing the service life of the finished tunnel beyond that established in the project (100–120 years) and reducing structural risks associated with durability during the service phase. In this regard, it is well known that the use of a suitable C_f of fibres improves the control of crack widths (Pujadas et al., 2012). Moreover, the risk of corrosion processes and related effects such as spalling is lower in fibre-reinforced concrete elements than in those reinforced with steel bars; in fact, such effects are almost non-existent with FRC (ACI, 2010). However, the authors decided to dispense with these issues since, while the experience to date with FRC in tunnels has been satisfactory, the technical literature detailing exactly how to quantify the benefits already discussed is still limited, and thus any assessment of the FRC solution would lack sufficient objectivity.

The life cycle analysis (LCA) stages considered were as follows: (1) extraction, transportation, receiving, and in-plant processing of the materials used to fabricate tunnel linings; this implies all the concrete components (cement, aggregates, water and additives) and reinforcing materials (steel bars and/or fibres), (2) fabrication and storage of the segments, (3) transport and installation of the segments, and (4) maintenance that may be needed to repair defects detected during the transitional stages (manufacture, transportation and installation). Other phases, such as maintenance in normal use (provided initial defects have been repaired) and the eventual deconstruction of the tunnel, are not considered to be determining factors in an evaluation of the type of concrete and type of reinforcement used in the lining segments.

Based on the results of the seminars, 1.0 km tunnel was considered to be representative to integrate all those factors involved in assessing the sustainability of the segment, omitting consideration of infrastructure and other elements not crucial to the analysis, such as vertical shafts and stations. The various different viewpoints and issues that might be brought up by industry representatives or public stakeholders, (for example, a precast segment manufacturer or decision maker from the public sector) could potentially alter the sustainability index of the various solutions. Thus, potential stakeholder preferences were considered by elaborating different weighting scenarios.

2.3. Requirements tree

The *requirements tree* comprises 3 requirements (R), 6 criteria (C), and 9 indicators (I) (Table 1). The indicators are independent of each other to avoid overlaps in the evaluation process. Similarly, the indicators included are those considered most representative in terms of assessing the sustainability index (I_s) of each alternative type of segment that meets the same geometric and technical specifications, such as ring diameter and thickness, and service live and maximum loads, respectively.

Weights (λ) were assigned using the AHP method, as other authors did in previous research (Sapuan et al., 2002; Hambali et al., 2009; AL-Oqla et al., 2015), and the results were rounded to the nearest multiple of 5. These weightings allow to establish the relative importance of each element in the requirements tree (Table 1). The base scenario (E_0) represents the view that economic and environmental factors are those with the greatest weight ($\lambda_{R1} = 40\%$ $\lambda_{R1} = 45\%$, respectively). This viewpoint reflects two key factors: the need to promote an environmental sensitivity, and an awareness of the impact these structures may have on future generations in terms of availability of resources and quality of life. While social aspects are taken into account, these are weighted to a lesser degree ($\lambda_{R3} = 15\%$) because it

Table 1
Requirements tree for the sustainability assessment of precast concrete segmental linings for TBM tunnels.

Requirement	Criteria	Indicator	Units	Function
R_1 economic (λ_{R1} = 40%)	C_1 direct costs (λ_{C1} = 90%)	I_1 total costs (λ_{I1} = 100%)	M€/km	DS
	C_2 cost of repairs (λ_{C2} = 10%)	I_2 probability of repair (λ_{I2} = 100%)	Attributes	
R_2 environmental (λ_{R2} = 45%)	C_3 resources consumption (λ_{C3} = 30%)	I_3 cement and aggregates (λ_{I3} = 50%)	Ton/km	DCx
		I_4 water (λ_{I4} = 20%)		
		I_5 steel reinforcement (λ_{I5} = 30%)		
	C_4 emissions (λ_{C4} = 40%)	I_6 CO_2 emissions (λ_{I6} = 100%)	TonCO$_2$-eq/ km	DS
	C_5 energy (λ_{C5} = 30%)	I_7 embodied energy (λ_{I7} = 100%)	MWh/km	
R_3 social (λ_{R3} = 15%)	C_6 labour conditions (λ_{C6} = 100%)	I_8 noise pollution (λ_{I8} = 30%)	Db	DCx
		I_9 risks during handling (λ_{I9} = 70%)	Attributes	

DS: decreasing S-shape; DCx: decreasing convex.

is assumed that requirements are already being met that ensure a suitable working environment and appropriate safety standards. Today, this base scenario would represent the viewpoint of an authority with a high degree of environmental sensitivity in a developed country in the midst of a good or very good economic situation.

The distribution of weightings shown in Table 1 represents a desirable scenario and one that should be promoted. However, it may not aptly represent certain viewpoints that might prevail in situations that differ from those described above. Therefore, a sensitivity analysis of the weightings that reflects other possible scenarios have been performed in this research. Section 3.4 presents the result of this analysis.

The *economic requirement* (R_1) is represented by two criteria: *direct costs* (C_1) and *repair costs* (C_2):

- C_1 is defined by a single indicator, *total costs* (I_1), which integrates the costs associated with all the different stages of lining segment production represented in the LCA. The costs of the plant and its installation and of the amortisation of the elements associated with manufacture and handling of the segments could also be included in R_1 to estimate the total cost of the concrete (per m^3, for example) or of the production of each ring. However, since such costs are rarely a decisive factor when comparing different concrete and reinforcement alternatives for tunnel segment, these can be safely ignored. The same consideration applies to the cost of the TBM. Finally, it should be noted that the different reinforcement solutions for precast segments are generally economically competitive, particular when the design has been optimised. As a result, reliable data from the manufacturers is needed to ensure a robust economic analysis. Should other relevant economic aspects not mentioned be taken into account in a specific study case, these must be included within this indicator.
- C_2, by means of the *repair probability indicator* (I_2), is used to qualitatively assess costs associated with the repair of any defects that might appear during any of the transitional phases taking into account the probability of such defects according to the type of reinforcement used. Such defects do not usually compromise the structural integrity of the ring in terms of withstanding external loads and, in general, damaged segments can be safely used. Repair

is nonetheless required since defects do affect the quality and durability of the element. It is well known that segments fabricated using certain reinforcement solutions are less prone to cracking than others under the same conditions (ACI 544.5R-10, Caratelli et al., 2012; de la Fuente et al., 2012; Meda and Rinaldi, 2014). Currently, no data or methods have been published that would allow us to objectively assess the risks discussed above according to the type of reinforcement used. In any case, based on the experience of the seminar participants in manufacturing segments and tunnel construction, an initial proposal was made for an evaluation based on attributes, which can be revised and improved in the future.

The three criteria in the *environmental requirement* (R_2) are the *consumption of natural resources* (C_3), *emissions* (C_4) and *energy consumption* (C_5) associated with the different LCA stages:

- The purpose of criterion C_3 is to evaluate total consumption of materials from natural sources and identify solutions that would minimise such consumption. To this end, three indicators were defined: *cement and aggregates* (I_3), *water* (I_4) and *steel reinforcement* (I_5). Indicator I_3 represents the amount by weight of cement and the aggregates, without distinguishing the components and precedence. Obviously, total consumption of water and energy, and emissions associated with processes for making cement differ from the values associated with aggregates, and these factors are thus taken into account by the respective indicators. Indicator I_4 is used to assess the degree of satisfaction associated with each solution in relation to total water consumption (concrete components and reinforcement). In this regard, the parametric studies carried out for this research concluded that more than 60% of the water consumption is associated to the steel reinforcement production and manufacturing. Finally, the indicator relating to *steel reinforcement* (I_5), bars and/or fibres, is also taken into account in the sustainability analysis. The weight assigned to this indicator (λ_{R5} = 30%) is less than that assigned to I_3 (λ_{R3} = 50%). This is because the steels used to reinforce concrete, although more scarce than the aggregates used to produce the concrete, contain as much as 60% recycled steel. Other types of fibres with different materials could also be considered as structural reinforcement of concrete (e.g., polypropylene, polyurethane, and glass). Nevertheless, these are disregarded in this indicator for the following reasons: (1) still there not exist real cases in which these fibres has been used as solely reinforcement and (2) the constituent materials of these fibres are synthetic and, thus, its use do not imply relevant impacts in terms of natural scarce resources (which is the main objective of the criteria C_3). However, in case of using these type of fibres, the environmental impact associated must be assessed in terms of the indicators I_7 and I_8 described below. Finally, it should be emphasized that polypropylene microfibres are commonly used for early shrinkage cracking control and fire performance enhancement of the concrete. These fibres are considered non-structural and, consequently, taken into account within indicators I_1, I_7 and I_8.
- C_4 and C_5, the most fundamental criteria in any analysis of environmental impact, are represented by the indicators *CO_2 emissions* (I_7) and *embodied energy* (I_8). The value functions assigned to each indicator are intended to favour concrete and reinforcement solutions that minimise both CO_2 emissions and embodied energy and are respectful of the environment and energy sources. The following items were included in the LCA to quantify both indicators: (1) extraction of materials, (2) treatment of materials, (3) segment fabrication, and (4) segment transport. Consumption associated with the installation, operation and maintenance of the TBM is not considered in the analysis because it is not influenced by and does not dis-

criminate between the different types of concrete or reinforcement used in the precast segments. Similarly, consumption associated with the repair of segments damaged in the transitional phases was not taken into account because such consumption represents residual values several orders of magnitude lower in terms of environmental impact than those of the values involved in the other phases analysed.

Finally, in *social requirement* (R_3), the criterion *labour conditions* (C_6) was evaluated by way of two indicators:

- The indicator *noise pollution* (I_8) varies according to the type of concrete used. For instance, solutions relying on the use of self-compacting rather than traditional concrete are associated with significantly lower noise levels in the work environment because the traditional method requires strong vibration energy to ensure compaction of the material, and this generates substantial noise pollution, making hearing protection mandatory for workers operating in the vicinity of the concrete pouring area.
- The *risks during handling* (I_9) of the segments, particularly the risk to workers of cuts and lesions when fibres on the surface of the segment protrude and are liable to cause injury. While surface polishing and inspection are always carried out, the risk increases with the C_f and when metal fibres are used since these are sharper and more rigid than plastic fibres. In the absence of more precise criteria and statistical data, this indicator was evaluated on the basis of attributes that were ranked in the seminars by the technicians with experience in plants producing precast segmental linings and by others with experience in TBM operation, two situations in which the workers may have to handle or touch the segments and are thus exposed to the risks described above.

To evaluate the sustainability index (I_s) of each alternative solution, *value functions* assigned using the method previously proposed (Alarcon et al., 2001; San-Jose Lombera and Garrucho Aprea, 2010; San-Jose Lombera and Cuadrado Rojo, 2010; Reyes et al., 2014; Hosseini et al., 2015) were used. The generic form of a value function is represented by Eq. (1), which allows to assess the sustainability (satisfaction) associated with each indicator (I_{ind}) by transforming the physical units to a dimensionless value between 0.0 and 1.0.

$$I_{ind}(X) = A + B\left[1 - e^{-K_i\left(\frac{|X_{ind}-X_{min}|}{C_i}\right)^{F_i}}\right]$$

(1)

In Eq. (1), B is the value of I_{ind} for X_{min}; X_{min} is the minimum abscissa value in the indicator interval assessed; X is the abscissa value for the indicator assessed; P_i is a shape factor which defines whether the curve is concave ($P_i < 1$), convex ($P_i > 1$), linear ($P_i = 1$) or S-shaped ($P_i > 1$), see Fig. 4; C_i approximates the abscissa at the inflexion point; K_i tends towards I_{ind} at the inflexion point; B, the factor that prevents the function from exceeding the range (0, 1), is obtained by Eq. (2), X_{max} being the abscissa value of the indicator that gives a response value of 1 for increasing value functions.

$$B = \left[1 - e^{-K_i\left(\frac{|X_{max}-X_{min}|}{C_i}\right)^{F_i}}\right]^{-1}$$

(2)

The form of the value functions assigned to each indicator (see Table 1) is a decreasing S-shape curve (DS) for I_1 and I_6–I_7 and a decreasing convex curve (DCx) for I_3–I_5 and I_8.
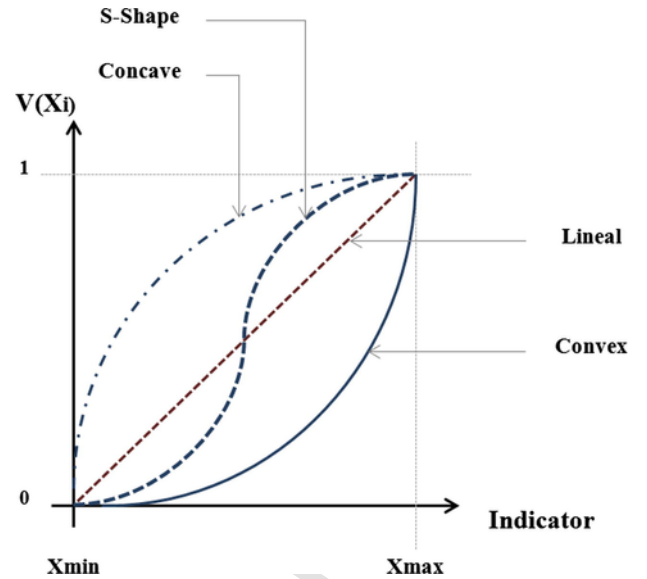

Fig. 4. Possible forms of the value function.

3. Case study: FGC extension tunnel to Terminal 1 at Barcelona Airport

3.1. Introduction and objective

The project drawn up in 2009 to connect the Prat de Llobregat FGC station with Barcelona Airport (INECO, 2009) includes a 2.84 km long tunnel bored using a TBM 10.60 m in diameter. The infrastructure improves connectivity with the high speed rail line connecting Madrid, Barcelona and the French border.

The design calls for a tunnel lining (Fig. 5a) comprising a universal ring with a mean length of 1.60 m and an internal diameter of 9.60 m. The ring is 0.32 m thick and is composed of 6 segments and 1 key.

The initial project proposes concrete segments reinforced with B500SD steel bars (f_{yk} = 500 N/mm^2) and concrete with a characteristic compressive strength value f_{ck} of 45 N/mm^2. This f_{ck} value is set to guarantee sufficient strength to withstand the flexural compression that occurs in the service phase when the cross section is subjected to the soil pressure. The designers also verified that the design forces do not exceed the cracking strength of the segment in any of the loading stages and fixed a minimum reinforcement of 13Φ12 mm on each side (Fig. 5b) to ensure adequate ductile behaviour in a hypothetical failure. The concrete cover (*c*) must be greater than 4 cm to protect the reinforcement from possible chemical attack. It should be noted that the layout of the tunnel passes under industrial areas where aggressive groundwater may be present.

The initial proposal specified rings composed of segments made with conventional reinforced concrete (CRC). However, while the project has been approved, the green light to start construction on the tunnel has not yet been given. Moreover, in view of the economic problems affecting Spain since 2009 and particularly as a result of the approval in the Spanish EHE - 08 (CPH, 2008) of FRC as a structural material, two new solutions for the segments using only structural fibres were proposed: (1) using conventionally vibrated FRC concrete and (2) using self-compacting fibre-reinforced concrete (SC-FRC).

In this research project, the method described in Section 2 to assess the sustainability of each of the three alternatives has been used. This analysis made it possible to minimise subjectivity in the deci-
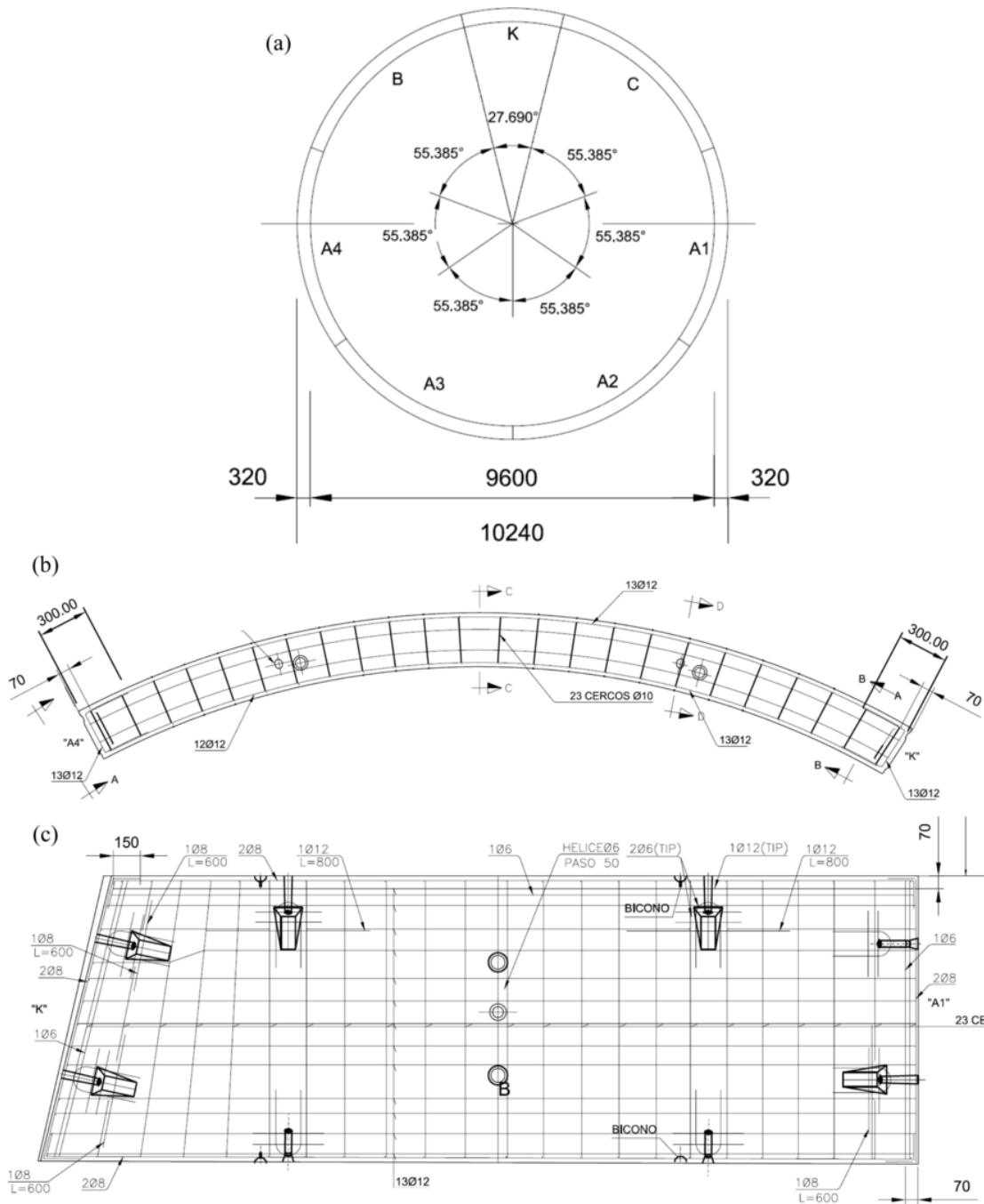
Fig. 5. (a) Ring configuration and (b) frontal section view and (c) top view of reinforcement cage.

sion-making process and take into account the issues and preferences of the different stakeholders. Furthermore, segments designed and manufactured using different types of materials have been tested at the Luis Agulló Structures and Materials Technology Laboratory (LATEM) at the UPC to check its structural suitability (Liao et al., 2015a,b).

3.2. Design of the concrete reinforcing structures of the segments

Table 2 shows the dosages used in the fabrication of the different types of concretes considered for the production of the segments. Two aspects of this process are of particular interest: (1) While the

Table 2
Dosages (in kg/m^3) considered for the different concrete mixes.

Materials	CRC	FRC	SC-FRC
CEM I 52.5	315	315	381
Sand 0/5	817	817	1.200
Fine aggregate 5/12	404	404	500
Coarse aggregate 12/20	810	810	200
Water	150	156	165
Superplasticiser	2.80	2.80	4.60
Steel fibres	0	50	45

same granular skeleton was used for the CRC and the FRC, the incorporation of fibres in the FRC reduces the workability of the mixture and this is offset by increasing the vibration time in the mould. (2) The fine fraction (cement, sand 0/5, and fine aggregate 5/12) used in the SC-FRC (2081 kg/m^3) is 36% greater than that of the CRC and FRC (1536 kg/m^3) in order to guarantee the self-compactability of the SC-FRC. For the same reason, the dose of superplasticiser used in the SC-FRC was 50% (4.60 kg/m^3) greater than that used in the CRC and FRC (2.80 kg/m^3).

The reinforcement solutions were different in each case. For the CRC segments (CRCS), the total amount of steel bar used was 110 kg/m^3 (Fig. 5b). To assess the mechanical requirements for FRC segments (FRCS) and for SC-FRC segments (SC-FRCS), the numerical model Analysis of Evolutionary Sections (AES) (de la Fuente et al., 2012c) was used, considering the same design values for axial forces (N_d) and bending moments (M_d) that had been estimated in the initial project and using the constitutive equation accepted in the MC-2010 to simulate the tensile behaviour of the FRC. From this analysis, the required characteristic values of residual flexural tensile strength for crack widths (CMOD) of 0.5 mm ($f_{R1k} = 3.8$ N/mm^2) and 2.5 mm ($f_{R3k} = 4.9$ N/mm^2) were obtained. Thus, the strength class of the FRCs is 4.0d ($f_{R1k} = 4.0$ N/mm^2 and $1.1 \leqslant f_{R3k}/f_{R1k} < 1.3$) according to the classification proposed in the MC-2010.

The fibres used were MasterFiber 502 with hooked-end anchors and a length of 50 ± 5 mm, a diameter of 1.0 ± 0.1 mm, and an elastic limit of 1000 N/mm^2. To characterise the flexural tensile behaviour of the FRCs, three – point notched beams measuring $600 \times 150 \times 150$ mm^3 were tested in accordance with EN 14651 (CEN, 2005). To optimise the value of C_f, values of 30, 45 and 60 kg/m^3 were considered in the production of the prismatic beams. The results showed that 50 kg/m^3 was the dosage required for CRC and 45 kg/m^3 for SC-FRC to achieve strength class 4.0d. SC-FRC requires 10% less fibre material than CRC because of the better orientation of the fibres in the pouring process of the self-compacting concrete due the flow forces and boundary conditions imposed by the walls of the mould. The same phenomena are observed in the full-scale element (Ferrara and Meda, 2006; Grünewald, 2004; di Prisco et al., 2013).

In terms of workability, slump values of less than 5 cm for CRC and FRC with the Abrams cone test (CEN, 2009a) were obtained, being this fact an indication of very dry concrete; however, the vibration energy generated in the segment moulds is sufficient to adequately compact these concrete mixes. Likewise, values of 65–68 cm obtained in the slump flow testing (CEN, 2010) for the SC-FRC confirmed the sufficient flowability to facilitate the self-compacting process.

Finally, the mean compressive strength (f_{cm}) values obtained at 1, 7 and 28 days with cylinder specimens $300 \times \Phi150$ mm^2 in accordance with test (CEN, 2009b) were very similar for the different concrete mixes, reaching values of $f_{cm,1} = 20.2$ N/mm^2, $f_{cm,7} = 53.0$ N/mm^2 and of $f_{cm,28} = 64.5$ N/mm^2. These results reflect that the specified f_{ck} of 45 N/mm^2 is reached.

3.3. Evaluation of the indicators

The construction of the tunnel lining involves 12,425 segments (1775 rings), requiring 28,322 m^3 of concrete. The segments will be fabricated in an existing plant specifically designed for the purpose; thus, the installation and maintenance cost of the plant and the components are included within the cost of the segments. The distance from the plant to the TBM access shaft is 110 km. The plant is expected to be in operation for a period of 16 months between the start

of preparations and final shutdown. It is estimated that the fabrication of all segments will take nine months with two 8-h work shifts a day.

The following is the information needed to assess the phases included in the first indicator I_1: (1) investment in the plant, (2) materials and equipment for the manufacture of the segmental linings, (3) personnel involved, (4) auxiliary equipment, (5) consumables, and (6) transport. Values were provided by the company manufacturing the segments. However, for this specific study case, the aspects that represented a relevant difference in cost depending on the solution used to fabricate the segments are the following: (1) the cost of materials for the manufacture of concrete (Table 2), (2) the reinforcement solution used (bars or fibres), and (3) the personnel required for the preparation of the reinforcement (2 per shift for CRCS and none for FRCS and SC-FRCS).

The evaluation of indicators I_3 and I_5 is based on the consumption of materials shown in Table 2, taking into account that the CRCS use 110 kg/m^3 of steel bars. The estimate for indicator I_4 is calculated by applying the values in Table 2 for the concrete manufacture and using the values for water consumption associated with the production of steel bars and fibres from (Guo and Fu, 2010).

The emissions of CO_2-eq (I_6) and energy (I_7) involved in the LCA processes of the materials used in the concrete were calculated using the mean values listed in the Inventory of Carbon Energy version 2.0 (ICE, 2001). The estimation of indicator I_6 for bars and steel fibres is based on (ICE, 2001) and (ITAtech, 2015).

Finally, indicators I_2, I_8–I_9 were evaluated in the seminars, taking into account the following: (1) the information contained in (ITAtech, 2015) to establish the probability of a segment needing repairs depending on the type of reinforcement (I_2); (2) the information on workplace noise pollution in precast plants and the health risks described in (Pons and de la Fuente, 2013) to evaluate I_8; and (3) the arguments set out in (Casanovas et al., 2014) to define indicator I_9 and specify how it should be assessed.

As described above, each indicator for each of the three segmental lining solution was assessed and the results are gathered in Table 3.

The conclusions that can be derived from the results presented in Table 3 are as follows:

- The use of FRCS (2.60 M€/km) represents a cost saving of 10.0% over CRCS (2.89 M€/km) and 0.4% over SC-FRCS (2.61 M€/km). These differences arise from differences in: (1) materials costs (concrete and steel) of 159.4, 135.9 and 136.5 €/m^3 for the concrete used in CRCS, FRCS and SC-FRCS, respectively; and (2) the manufacturing costs associated with the fabrication of the segments, estimated at 67.2 €/m^3 for CRCS and 62.1 €/m^3 for FRCS and SC-FRCS (a 7.6% reduction compared to CRCS because of labour associated with the use of steel bar reinforcement).
- The use of SC-FRCS (64,603 Ton/km) also results in a saving of 2.8% in the consumption of cement and aggregates in the concrete as compared to the CRCS and FRCS solutions, with 66,444 Ton/

Table 3
Indicator values (X_i) obtained for each alternative.

Indicator	CRCS	FRCS	SC-FRCS
I_1 direct costs (M€/km)	2.89	2.60	2.61
I_2 probability of repair	Moderate	Low	Low
I_3 cement and aggregates (Ton/km)	66,444	66,444	64,603
I_4 water (Ton/km)	15,590	10,863	11,668
I_5 reinforcing steel (Ton/km)	1097	499	449
I_6 CO_2 emissions (TonCO_2-eq/km)	5305	4601	5083
I_7 embodied energy (MWh/km)	12,411	9375	9904
I_8 noise pollution (Db)	90	90	60
I_9 risk during handling	Reduced	High	High

km for both. The water consumption required in the manufacture of FRCS (10,863 Ton/km) (associated with the manufacture of the steel and the concrete) is some 30.3% lower than in the CRCS segments (15,590 Ton/km), and 6.9% lower than in the SC-FRCS solution. Finally, the manufacture of SC-FRCS (449 Ton/km) represents a saving in steel of 59.1% over the CRCS solution (1097 Ton/m^3) and of 10.0% compared with FRCS.

- FRCS (4601 $TnCO_2$-eq/km) produces 13.3% and 9.5% lower emissions compared to the CRCS (5305 $TnCO_2$-eq/km) and the SC-FRCS (5083 $TnCO_2$-eq/km) solutions, respectively, due to the lower consumption of cement and steel in the reinforcement. Furthermore, FRCS (9375 MWh/km) is the solution that requires the least energy throughout the entire LCA, some 24.5% lower than CRCS (12,411 MWh/km) and 5.3% lower than SC-FRCS (9904 MWh/km).

3.4. Sustainability indices I_s for each alternative

The constitutive parameters for each value function (Table 4) were agreed during the seminars, drawing on the experience of the experts complemented by criteria presented in the literature on MIVES and the values of X_i obtained for the three alternatives studied (Table 3). These values could be established as reference for future analysis; however, other values can be adopted according the stakeholders' preferences.

Once all of the elements involved have been represented in the sustainability analysis—the requirements tree (Table 1), values X_i for each segment fabrication solution (Table 3), and the constitutive parameters of the value functions (Table 4)—the sustainability indices I_s for each segment solution can be calculated (Table 5) for the base scenario E_0 (λ_{R1} = 40%, λ_{R2} = 45% λ_{R3} = 15%).

The results presented in Table 5 show that the solutions that use structural fibres as an alternative to steel bars result in a higher I_s value. Specifically, SC-FRCS (0.812) represents an increase of 34% in I_s over CRCS (0.605) and an increase of 8% over FRCS. The better performance in terms of sustainability of the SCFRCS solution is a result of two factors: the use of fibres rather than steel bars, a

Table 4
Constitutive parameters for defining the value functions.

Indicator	X_{max}	X_{min}	C	K	P
I_1 Direct costs (M€/km)	4,00	2,24	1,00	1,00	2,50
I_2 Probability of repair	Steel: 0.00–0.25 (very high); low fibre content: 0.25–0.50 (high); steel + low fibre content: 0.50–0.75 (moderate); High fibre content: 075–1.00 (low)				
I_3 Cement and aggregates (Ton/km)	70,000	65,000	67,000	0.10	2.50
I_4 Water (Ton/km)	29,000	7500	15,000	0.10	2.50
I_5 Reinforcing steel (Ton/km)	1350	450	800	1.00	2.50
I_6 CO_2 emissions ($TonCO_2$-eq/km)	7800	3800	5000	2.50	200
I_7 Embodied energy (MWh/km)	18,500	7500	10,000	2.50	2.00
I_8 Noise pollution (Db)	150	0	80	3.00	10.00
I_9 Risks during handling	Very high: 0.00–0.25; High: 0.25–0.50; Acceptable: 0.50–0.75; Reduced: 0.75–1.00				

Table 5
Values of I_s and I_R obtained for each alternative.

	CRCS	FRCS	SC-FRCS
I_s	**0.605**	**0.754**	**0.812**
I_{R1}	0.703	0.899	0.909
I_{R2}	0.513	0.786	0.836
I_{R3}	0.620	0.270	0.480

choice that reduces both overall costs and environmental impact; and the use of self-compacting concrete, which leads to a better distribution of the fibres and better mechanical performance than can be achieved with traditional FRC.

To analyse the sensitivity of the results obtained (Table 5), three additional scenarios were considered as follows:

- E_1 (λ_{R1} = 33%, λ_{R2} = 33%, λ_{R3} = 33%) simulates a reasonable view of all the requirements involved in the analysis and represents sustainability in the strict sense.
- E_2 (λ_{R1} = 75%, λ_{R2} = 10%, λ_{R3} = 15%) assigns greater weight to the economic requirement I_{R1} in order to simulate a more entrepreneurial view of the analysis or take into account a situation of financial crisis on the part of the authority or agency that has to take the decision and make the investment. In any case, this scenario must be considered in any analysis because, although it may be realistic, it is, nonetheless, unacceptable from the standpoint of sustainability.
- E_3 (λ_{R1} = 25%, λ_{R2} = 60%, λ_{R3} = 15%) gives particular weight to the environmental requirement I_{R2} in order to prioritise solutions respectful of the environment based on use of available resources and respectful of society today and in the future. This scenario could represent the vision of a public authority with a high environmental sensitivity and, in general terms, a situation of economic growth.

To facilitate the analysis and interpretation of the results, in these three scenarios the same weight values for the criteria (λ_C) and indicators (λ_I) as those used in scenario E_0 (Table 1) were maintained. The constitutive parameters of the value functions are also maintained (Table 4). The resulting values of I_R considered in the sensitivity analysis are shown in Table 5. It should be noted that in a more rigorous analysis of sensitivity or cases in which the ranges of values for I_s and I_R of the alternatives are more tight, the use of statistical techniques are recommended to ensure robust results (del Caño et al., 2012). Table 6 shows the values of I_s for each of the scenarios.

The results shown in Table 6 reveal the following:

- All the alternatives present the highest value for I_s in the scenario that gives greatest weight to the economic requirement (E_2), showing that all the solutions studied should generate a high level of satisfaction in economic terms. Nevertheless, all the solutions present values of I_s under 0.900, confirming that there is still room for improvement in the fabrication of FRC segments.
- SC-FRCS is the solution that presents high values for I_s in all the scenarios. The ranking of alternatives is the same as that obtained for scenario E_0. Nevertheless, it should be highlighted that for scenario E_2 (economic), FRCS presents a I_s scarcely 1.0 higher than

Table 6
Values of I_s derived from the sensitivity analysis.

	CRCS	FRCS	SC-FRCS
E_0	**0.605**	**0.754**	**0.812**
E_1	0.606	0.645	0.734
E_2	0.783	0.793	0.924
E_3	0.577	0.737	0.801

CRCS. Therefore, in this situation the investment required to change from the CRCS formerly proposed within the project to FRCS would not be attractive.

- Comparison of FRCS and CRCS shows that the total replacement of rebar for structural fibres in vibrated concrete yields to an increase of I_s between 1% (E_1) and 28% (E_3).
- Comparison of SC-FRCS and FRCS reveals that the use of self-compacting concrete gives rise to an increase in values of I_s of between 8% (E_2) and 17% (E_1).

4. Conclusions

In this paper a model for assessing the sustainability of different concrete and reinforcement alternatives to be used in precast concrete lining segments for tunnels excavated using a TBM is proposed. The model is based on the MIVES method and it allows stakeholders comparing and prioritising alternative solutions while minimising the subjectivity in the decision-making process. The elements that compose the model were agreed and calibrated carrying out seminars in which experts from companies that manufacture segments and construct TBM tunnels participated.

The method proposed is general and can be used for any ring geometry, concrete and reinforcement configuration. As real study case, the method has been used to assess the sustainability of different alternatives of concretes (conventional or self-compacting concrete) and reinforcement configurations (steel bars or fibres) of a 2.84 km segmental lining constructed in Barcelona. The conclusions drawn from the sustainability indices I_s obtained for this specific study case are as follows:

- Full replacement of the steel bars (minimum amount for ductility requirement) by structural fibres (dosage depending on the concrete type) yields higher values of I_s in all the scenarios under study. This conclusion can be extended to cases in which the risk of cracking is low in both the transitional stages (reduced tensile flexural stresses) and the service phase (ring compressed by soil pressure).
- The use of SC-FRC increases the value of I_s over FRC at least 8% for the following reason: although the cost of the SC-FRC concrete mix is some 15% higher than that of FRC, the greater spatial efficiency of the fibre distribution in the case of SC-FRC reduces by 10% the quantity of fibres required to achieve mechanical characteristics equivalent to those of FRC. Likewise, the use of SC-FRC allows reducing the noise pollution in the precast plant, aspects that can be quantified and integrated into the proposed model.

These conclusions are particular for this specific tunnel; however, these can be extrapolated to other tunnels with similar conditions in terms of ring geometry and low probability of cracking during transient loading situations. Contrarily, the full replacement of the steel rebars for structural fibres could not be sustainable when high loads are expected; in these cases, traditional reinforced concrete alternatives or even hybrid solutions (steel bars and fibres) are more suitable.

Finally, the model presented herein can serve as a tool for decision making on similar projects. In this regard, the model permits to adapt the distribution of weights to other stakeholders' preferences different from those considered in this research as well as to include other indicators.

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